Voltage and Frequency Controller for Three Phase Four Wire Isolated Double Wind Energy Conversion System using Cage Generators

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Abstract—**This paper presents a new voltage and frequency Controller for three phase four wire isolated double wind energy conversion system using one squirrel cage induction generator (SCIG) driven by a variable-speed wind turbine and another SCIG driven by a constant power wind turbine feeding three phase four-wire local loads. The proposed system consist two back to backconnected pulse width modulation controlled insulated gate bipolar transistor based voltage source converters (VSCs) with a battery energy storage system at their dc link. The main purpose of the control algorithm for the VSCs is to achieve control of the magnitude and the frequency of the load voltage. The proposed system has a capability of bidirectionalactive and reactive power flow, by which it controls the magnitude and the frequency of the load voltage. In this system wind turbineand a voltage and frequency controller are modeled and simulated in MATLAB using Simulink and Sim Power System set toolboxes and various aspects of the proposed system are studied for different types ofloads, and under varying wind speed conditions. The performance of the proposed system is presented todemonstrate its capability of voltage and frequency control (VFC) and load balancing.**

Keywords – Battery energy storage system (BESS), Wind energy conversion system, Squirrel cage induction generator (SCIG).

I.INTRODUCTION

Due to souring prizes of fossil fuels and increase in emission of greenhouse gases, the reasonableattention given to the renewable energy sources.Renewable energy sources are the natural energyresources that are inexhaustible, for example, wind, solar,geothermal, biomass, and small hydrogeneration.

As considering wind turbines, they are consisting of two types of wind turbine generators fixed speed and variable speed turbinein which rotational speedvaries inaccordance with wind speed. Theenergy-conversion efficiency of fixed speed wind turbine is very lowfor widely varying wind speeds.In early years, windturbinetechnology has switched from fixed speed to variablespeed. The features ofvariable speed machines are they reducemechanical stresses, dynamically compensate for torque andPower pulsations, and improve power quality and systemefficiency [1].

When the renewable energy sources are connected to the grid, the total active power is fed to the grid. Forisolated systems supplying local loads, if the extracted power ismore than the local loads (and losses), the excess power is supplied to a dump load orstored in the battery bank [1].

WhenSCIG is used for wind generation, its reactivepowerrequirement is met by a capacitor bank at its statorterminals. The SCIG has advantages like being simple, lowcost, rugged, maintenance free, absence of dc, brushless, etc.,

In this paper, a new three-phase four-wire isolated wind energy conversion system is proposed for isolated locations, which cannot be connected to the grid. The proposed system utilizes variable speed Wind-turbine-driven$SCIG_v$(subscript vfor variable speed wind), and a constant-speed/constant-power wind-turbine-driven$SCIG_C$(subscript *c* for constant-speed wind). For the rest of this paper, the subscript *v* is used to denote the parameters and variables ofthe variable speed wind-turbine generator, and the subscript *c* is used to denote the parameters and variables of the constant power wind-turbine generator.A battery energy storagesystem (BESS) is used in the dc link, which performs thefunction of load leveling in the wake of uncertainty in thewind speed and variable loads. In order to remove the ripplesfrom the battery current an inductor isconnected in series with the BESS.

A new control algorithm is proposed for the double wind energy conversion systemit has the capability of loadleveling, load balancing, along with voltage andfrequency control (VFC).

For the proposed system, there are three modes of operation. In the first mode, the required active power of the load is less than the power generated by the$SCIG_C$, and the excess power generated by the $SCIG_C$ is transferred to the BESS through the load-side converter. Moreover, the power generated by the $SCIG_v$ is transferred to the BESS.Second mode, the required active power of the load is morethan the power generated by the$SCIG_C$but less than the total power generated by $SCIG_v$and $SCIG_C$. Thus, portion of thepower generated by $SCIG_v$is supplied to the load through theload-side converter and remaining power is stored in BESS. Inthe third mode, therequired active power of the load is morethan the total power generated by $SCIG_v$and $SCIG_C$. Thus,the deficit power is supplied by the BESS, and thepowergenerated by $SCIG_v$ and the deficit met by BESS are suppliedto the load through the load-side converter.

II. PRINCIPLE OF OPERATION

This system uses two back to- back-connected PWM-controlled IGBT-based VSCs. These VSCs are referred to as the machine ($SCIG_v$) side converterand load-side converter. The objectives of the machine($SCIG_v$) side converter are to convert AC to DC, and the objectiveof the load-sideconverter is VFC at the load terminals bymaintaining active- and reactive-power balance..

The load-side converter is controlled for theregulation ofload-voltage magnitude and loadfrequency. To maintain theload-frequency constant, it is essential that any surplus activepower in the system is diverted to the battery. Also, thebattery system should be able to supply any deficit in thegenerated power. Similarly, the magnitude of the load voltageis maintained constant in the system bybalancing the reactivepowerrequirement of the load through the load side converter.

III. CONTROL ALGORITHM

A. Control of Machine Side Converter

The main purpose of the load-side converter is to convert AC into DC. It is used as a rectifier.

B. Control of Load-Side Converter

The main purpose of the load-side converter is to maintain rated voltage and frequency at the load terminals irrespective of connected load.

Generation of Reference Three-Phase Currents:

The reference voltages (V_{an}^*, V_{bn}^*, and V_{cn}^*) for the control of the load voltages at time *t* are given as

$$V_{an}^* = \sqrt{2}V_t \sin(2\pi f t) \quad (1)$$

$$V_{bn}^* = \sqrt{2}V_t \sin(2\pi f t - 120) \quad (2)$$

$$V_{cn}^* = \sqrt{2}V_t \sin(2\pi f t + 120) \quad (3)$$

where*f* is the nominal frequency, which is considered as 50 Hz, and V_t is the rms phase-to- neutral load voltage, which is considered as 240 V.

The load voltages (V_{an}, V_{bn}, and V_{cn}) aresensed andcompared with the reference voltages.The error voltages(V_{anerr}, V_{bnerr} andV_{bnerr}) at the nthsampling instant arecalculated as

Vanerr(n) ={V*an(n) – Van(n)} (4)
Vbnerr(n) ={V*bn(n) – Vbn(n)} (5)
Vcnerr(n) ={V*cn(n) – Vcn(n)} (6)

The reference three-phase $SCIG_C$ currents (i_{sca}^*, i_{scb}^*, i_{scc}^*) are generated by feeding the voltage error

$$i_{sca(n)}^* = i_{sca(n-1)} + K_{pv}(V_{anerr(n)} - V_{anerr(n-1)}) + K_{iv}V_{anerr(n)} \quad (7)$$

$$i_{scb(n)}^* = i_{scb(n-1)} + K_{pv}(V_{bnerr(n)} - V_{bnerr(n-1)}) + K_{iv}V_{bnerr(n)} \quad (8)$$

$$i_{scc(n)}^* = i_{scc(n-1)} + K_{pv}(V_{cnerr(n)} - V_{cnerr(n-1)}) + K_{iv}V_{cnerr(n)} \quad (9)$$

The reference three-phase $SCIG_C$ currents are thencompared with the sensed $SCIG_C$ currents (i_{sca}, i_{scb}, and i_{scc}) tocompute the $SCIG_C$ current errors as

$$i_{scaerr} = i_{sca}^* - i_{sca} \quad (10)$$

$$i_{scberr} = i_{scb}^* - i_{scb} \quad (11)$$

$$i_{sccerr} = i_{scc}^* - i_{scc} \quad (12)$$

These current errors are amplified and theamplifiedsignals are compared with a fixedfrequency (10 kHz)triangular carrier wave of unity amplitude to generate gatingsignals for IGBTs of the load-side converter.

IV. DESIGN OF SCIG-BASED DOUBLE WIND ENERGY CONERSION SYSTEM

The system is designed for an isolated location with theload varying from 30 to 90 kW at a lagging power factor (PF)of 0.8. The average load of thesystem is considered to be 60Kw.

A. Selection of Rating of SCIGs

The rating of the variable speed wind turbine is considered as 55Kwand that of constant speed wind turbineis taken as 35Kw.Both turbines arecoupled to SCIGs. Therating of the $SCIG_v$is equal to the rating of the variable speedwind turbine,which is 55kW. The rating of the $SCIG_c$ should be equal tothe rating of the constant speed wind turbine, which is 35kW.

B. Modeling of wind turbine

The mechanical power P_m captured by the wind turbine is

$$P_m = 0.5\, C_p\, \pi\, r^2\, \rho\, V_w^3 \quad (14)$$

Where C_p=coefficient of performance, r=radius of turbine,V_w=wind speed, ρ=density of air.

C.Selection of voltage of dc link and battery design

For satisfactory PWM control, the dc busvoltage(V_{dc}) must be more than the peak of the linevoltage [8]

$$V_{dc} = \left\{2\sqrt{\tfrac{2}{3}}V_{ac}\right\} m_a \quad (15)$$

wherem_a is the modulation index normally with a maximumvalue of one and V_{ac} is the rms value of the line

voltage on theac side of the PWM converter. The maximum rms voltage at$SCIG_v$ terminals as well as the rms value of the line voltage atthe load terminals is 415 V. Substitute the value ofac=415V,
the value of Vdc should be obtained as 677.7 V. The voltage ofthe dc link and the battery bank is selected as 700 V.
Battery is an energy storage unit, its energy isrepresented in kilowatt-hour, when a capacitor isused to modelthe battery unit, the equivalentcapacitanceC_b is given as[7].

$$C_b = \frac{kWh \times 3600 \times 1000}{0.5\,(V_{ocmax}^2 - V_{ocmin}^2)} \quad (18)$$

Where V_{ocmin} and V_{ocmax} are the minimum and maximumopen circuit voltage of the battery under fully discharged andcharged conditions. HereThevenin's model is used fordescribing the battery in which the parallel combination ofcapacitance (C_b) and resistance(R_b) in series with internalresistance(R_{in}) and an ideal voltage source of voltage 700VTaking the values of V_{ocmax} = 750V,V_{ocmin} = 680V, andkW · h = 600, the value of $C_b$obtained is 43156F.

D. Selection of Rating of Machine ($SCIG_v$) Side Converter

The maximum active-power flow through the machine side converter P_{sw} = 55 kW, and the maximum reactive power flow provided from the machine-side converter (Q_{sw}) is calculated as

$$Q_{sw} = \left\{\frac{V_{msc}^2}{2\pi f\, L_m}\right\} = 18.4\ kvar \quad (19)$$

Where V_{msc} is the maximum line voltage generated at the $SCIG_v$ terminals, which is 415 V, at a frequency(f) of 50 Hz generated at a wind speed of 11.2 m/s.

The V A rating ($V\,A_{msc}$) of the machine-sideconverter is calculated as

$$V\,A_{msc} = \sqrt{(P_{sw}^2 + Q_{sw}^2)} = \sqrt{(55^2 + 18.42^2)} = 58\text{kVA}$$

and the maximum rms machine-side convertercurrent as

$$I_{sw} = \frac{V\,A_{msc}}{(\sqrt{3V_{msc}})} = 80.7\ A.$$

The voltage rating of the switching devices is decided by the dc-link voltage, whose maximum value is 750V. Taking a 25% margin,the voltage rating of the switching devices of the machine-side

Converter should be more than 1.25 ∗750 V, i.e., 937.5 V.
The maximum current through the switching device is 1.25{0.05 ∗(√2) ∗80.7 + (√2) ∗80.7}A =149.8 A.
The ratings of the commercially available device (IGBT) higher than these values are 1200 V and 200A, and the same are selected for the design purpose.

E. Selection of Rating of Load-Side Convertor

The rating of the load-side converter is determined by the case when the connected load is at its maximum value, i.e., 90 kW at 0.8 lagging PF. The reactive power of the load is supplied by the load-side converter. Hence, the reactive power flow through load-side converter (Q_{lsc}) is equal to thereactive power demand of the load (Q_L). At a load of 90 kW at0.8 lagging power factor,

Q_{lsc} = Q_L= (90/0.8) × 0.6 = 67.5kvar.
Therefore, the kVA rating of the load-side converter(kVA_{lsc}) is

$$I_{lsc} = \frac{V\,A_{lsc}}{\sqrt{3V_{lsc}}} = 156.5A$$

Where V_{lsc} is the rms voltage on the ac side of theload side converter, which is 415 V.

The maximum current through the switching devices in the load-side converter =1.25 × (11.1 + 221.3) = 290.5 A.
The voltage rating of the switching devices is decided by the dc-link voltage, whose maximumvalue is 750 V. Taking a 25% margin, the voltagerating of the switching devices of the load-sideconverter should be more than 1.25×750 V, i.e., 937.5 V.
The commercially available rating for switching device (IGBT) higher than 937.5 V and 290.5 A is 1200 V and 300 A.

F.Selection of rating of AC inductor and RC filter on ac side of load-side converter

An inductor is used on the ac side of the load-side converter for boost function. For 5% ripple in the current through the inductive filter, inductance (L_f) of the inductive filter can be calculated as[8]

$$L_f = \{\left(\frac{\sqrt{3}}{2}\right) m_a V_{dc} / (6a f_s I_{r(p-p)lsc})\} \quad (19)$$

Where f_s= switching frequency=10kHz

$$L_f = 0.76\ mH$$

A high-pass first-order filter tuned at half theswitching frequency is used to filter out the noise from the voltage at the load terminals. The timeconstant of the filter should be very small compared with the fundamental time period (T), or RC <<T/10.When T = 20 ms, considering, C = 5μF, R can be chosen as 5Ω.

V. MATLAB BASED MODELING

A simulation model is developed in MATLAB using Simulink and Sim Power System set toolboxes. The developed MATLAB model for the double wind-energy conversion system is shown in Fig.1.

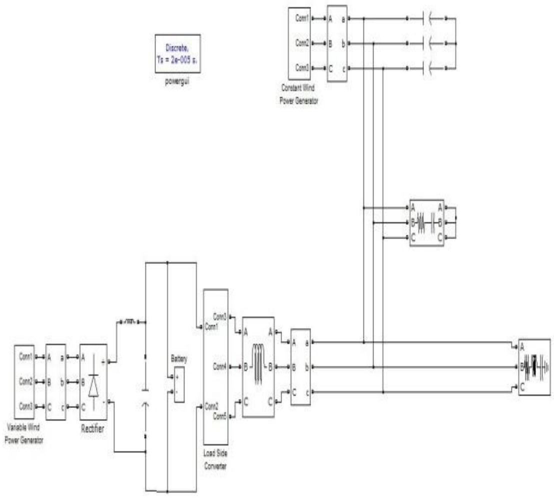

Fig.1. MATLAB simulation diagram of double wind energy conversion system.

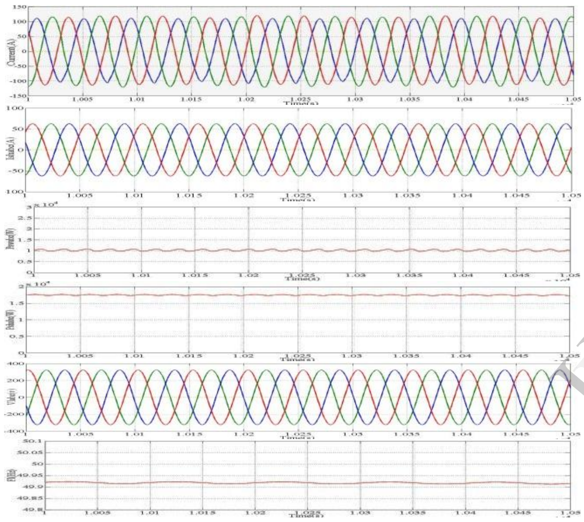

Fig.2. Performance of double wind energy conversion system with balanced linear load (60Kw) at wind speed of 11.2 m/s.

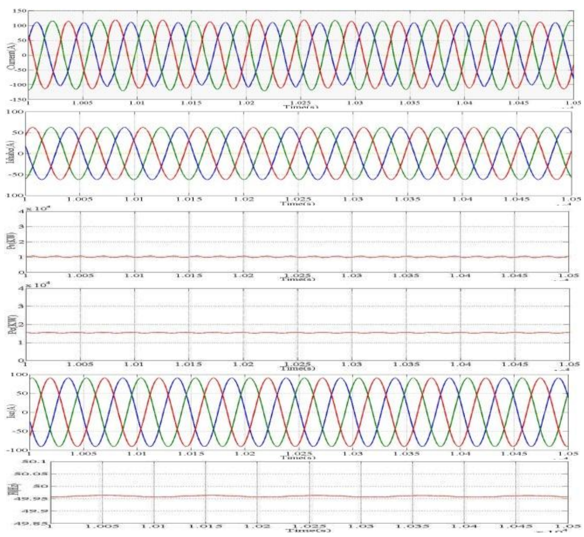

Fig.3. Performance of double wind energy conversion system with balanced linear load(100Kw)at wind speed of 11.2 m/s.

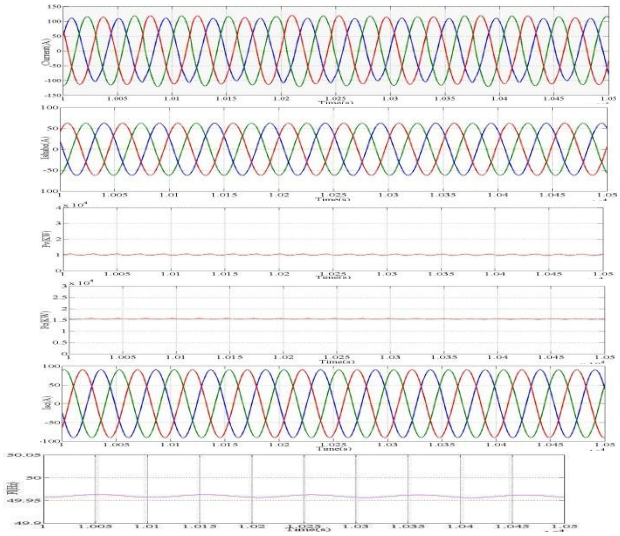

Fig.4. Performance of double wind energy conversion system with balanced linear load (20Kw)at wind speed of 8 m/s.

VI. SIMULATION RESULTS

The performance of the double wind energy conversionsystem with the proposed control algorithm is demonstrated under different dynamic conditions (various electrical conditions andmechanical conditions) as shown in Figs. 2-4. Moreover, performance of the double wind energy conversion system is studied with various electrical loads. Theperformance of the system is also studied under varying $SCIG_v$ rotor speeds due to wind speed variations .The simulated transient waveforms of the three phase$SCIG_v$stator current(Isv), $SCIG_c$ stator current(Isc),$SCIG_v$stator power(P_v),$SCIG_c$stator power(P_c),load voltage(V_L),load frequency(f_L)are shown for different operatingconditions. Thus it verifies the three modes of operation.

VII. CONCLUSION

Among the renewable energy sources, wind energy conversion system is more reliable source of energy.A new three-phase four wire autonomous double wind energy conversion system, using one cage generator driven by variable speed wind turbine andanother cage generator driven by constantspeed/constant power wind turbine along withBESS has been modeled and simulated in MATLAB usingSimulink and sim power system. Theperformance of thedouble wind energy conversion system has beendemonstrated under differentelectrical andmechanical dynamic conditions. It has beendemonstrated that the proposed double wind energy conversion system performssatisfactorily under different dynamicconditions whilemaintaining constant voltage and frequency. Moreover, it hasshown capability of load balancing.

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